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TOURING THE SATURNIAN SYSTEM

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The Cassini mission to Saturn employs a Saturn orbiter and a Titan probe to conduct an intensive investigation of the Saturnian system. The Cassini orbiter flies series of orbits incorporating flybys of the Saturnian satellites called tile. "sate.llilc tour". During the tour, the gravitational fields of the satellites are used to mortify and control the orbit, targeting from one satellite flyby to the next. The tour trajectory must also be designed to maximize opportunites for science observations, subject to mission-imposed constraints. Tour design studies have been conducted for Cassini to identify trades and strategic.s for achieving these sometimes conflicting goals. Concepts, strategies, and techniques previously developed for the Galileo mission to Jupiter have. been modified, and new ones have been developed, to meet the requirements of the Cassini mission,

1. INTRODUCTION

The Cassini mission will be the first 10 visit the Saturnian system in the more than two decades which will have elapsed since the Voyager flybys in 1980 and 1981. Cassini will conduct an intensive investigation of Saturn, its rings, sale.]li[cs, and magnetosphere for four years.

After its insertion into orbit about Saturn, the Cassini orbiter travels in a series of highly elliptical orbits about Saturn. This series of orbits is referred to as the "sate.iiite. [our". A large portion of the mission's scientific objectives arc accomplished during this portion of the mission, and the design of the tour trajectory is an important factor in achieving these. objectives.

The tour contains approximately 35-40 close., "targeted" flybys of Saturnian satellites. A targeted flyby is one where the orbiter's trajectory has been designed to pass through a specified aimpoint (latitude, longitude, and altitude) al closest approach, in order to use the satellite's gravitational influence to produce a desired change in the trajectory. Targeted flybys are capable of making large changes in the orbiter's trajectory. A single targeted flyby can change the orbiter's Saturn-relative velocity by hundreds of rids. For comparison, the total AV available from the orbiter's thrusters is about 5(K) m/s for the entire tour containing 35-45 encounters.

Each targeted flyby is used to target the orbiter to the next flyby. The abundance of aimpoints at each satellite encounter makes possible a large number of tours, each of which may satisfy many of the scientific objectives in different ways. While it is relatively easy to design a tour to satisfy any single scientific requirement, it is difficult 10 design a single, tour which completely fulfills all the requirements, because the trajectories needed to satisfy different scientific requirements are often dissimilar.

Tour design involves maximizing science return in competing scientific areas while satisfying mission-imposed constraints. "l"his is a complex task, as experience in designing satellite tours for the Galileo mission to Jupiter showed (Wolf and Byrnes, 1993; D'Amario, Bright, and Wolf, 1992). Tour design studies have been conducted for Cassini building on [he, wealth of experience gained from Galileo. Trades between areas of scientific interest and methods of meeting constraints arc examined here, and a sample tour is presented.

The Cassini spacecraft carries the Huygens atmospheric probe, which is released into the atmosphere of Titan. Upon arrival at Saturn, a maneuver is performed to siow the spacecraft and insert it into orbit about Saturn. Near the first apoapsis, another maneuver is performed which simultaneously raises the. periapsis distance from Saturn and targets the spacecraft 10 the desired flyby aimpoint at Titan. Closer 10 "l"i[an, the spacecraft (both orbiter and probe) is maneuvered onto a Titan impact trajectory. The orbiter then separates from the probe and performs a maneuver which deflects it away from impact onto the desired flyby trajectory. The probe continues on the impact trajectory, enters the atmosphere, and relays its data through the orbiter to Earth as the orbiter flies overhead. The probe mission is described in detail in Section 4. The orbiter continues on along the tour trajectory.

2. SCIENCE OBJECTIVES

The scientific investigations to be *performed* by the Cassini orbiter can be divided into five areas: Saturn, the Saturnian magnetosphere, Titan (Saturn's largest satellite), the icy satellites (those other than Titan), and the rings.

2.1 Saturn

Observations of cloud features and other dynamics in the Saturnian atmosphere can only be made of sunlit portions of Saturn. Observations at phase angles of 15 deg. or less for periods of 20 hours or more (two rotational periods of Saturn) are of particular interest to allow movies of the atmosphere to be made.

Radio science experiments as well as images can shed light on Saturn's atmosphere. When the orbiter passes behind Saturn as viewed from Earth, radio signals from the orbiter are not cut off. Instead, they are refracted by the dense Saturnian atmosphere on their way to Earth. Because a great deal of information on the atmosphere and magnetic field may be gleaned by analysis of the refracted polarized signals, passes behind Saturn are desired in the tour. Such passes are called occultations of Earth by Saturn, as viewed from the orbiter.

2.2 Magnetospheric Science

Mapping of the Saturnian magnetosphere is a high-priority goal. In order to achieve it, the spacecraft must cover as large as possible a region around the planet over as large a range of distances as possible.

Of particular interest are passages through the Saturnian magnetotail, which streams out from Saturn in a shape roughly resembling a windsock in the direction opposite the sun. The region of greatest scientific interest lies within 3 Saturn radii (RS) of the anti-sun line at distances of 40 RS or greater.

Also desired are passages through magnetic field lines intersecting the auroral region. The auroral region lies at approximately 75-80 north latitude, which means an inclination of 75-80 deg. must be achieved in order to pass through the field lines associated with the aurora.

Satellite "wakes" are created as charged particles trapped in Saturn's magnetic field sweep by the satellites. Saturn's magnetic field rotates with Saturn at a rate faster than the rotation rates of the satellites around Saturn. Therefore, the wakes stream out in front of each satellite. Several passages through Titan's wake are desired, as well as through the wakes of icy satellites. Wake passes are achieved with flybys near a satellite's equator over the satellite's leading edge. As the following discussion will show, such flybys reduce orbital period. Another region of interest is the "flux tube". Plasma moving by a satellite generates a wave in Saturn's magnetic field which propagates in a region located approximately over a satellite's poles, tilted toward the direction of motion of the satellite. Passages through flux tube regions are achieved by flying nearly over a satellite's pole.

2.3 Titan

Titan is Saturn's largest moon. A dense atmosphere hides its surface from view. Both the surface and atmosphere of Titan are of great scientific interest. The Cassini probe is designed to provide in-situ observations of the atmosphere. Radio-occultations of Saturn (passes of the orbiter behind Titan as viewed from Earth) are desired for the information they can provide on Titan's atmosphere. Several occultations are desired, with entry/exit points spread out over a wide range of latitudes and longitudes, allowing sampling of points throughout the atmosphere.

The Cassini orbiter carries a radar in order to map the surface of Titan. During each close approach, a radar swath is taken which covers a small portion of Titan's surface. In order to maximize the area mapped on Titan's surface, it is necessary to incorporate as many Titan flybys as possible in the tour, and to arrange them so that the spacecraft flies over different parts of the surface.

2.4 Saturn's other satellites

The satellites other than Titan are also objects of considerable scientific interest. Images of these satellites could contribute m the unlocking of some of the mysteries surrounding these bodies. The satellites of greatest interest arc. Iapetus, Enceladus, Dione, Hyperion, and Mimas. Iapetus' leading edge is much darker than its trailing edge, for reasons unknown. Enceladus has a particularly smooth surface, and Saturn's E ring has an increased particle density in the vicinity of Enceladus' orbit. Dione appears to have a diverse surface composition; its position in Saturn's magnetic field may offer an especially good chance to observe magnetospheric wake, interactions. Hyperion is irregularly shaped, and a close flyby is desired in order to accurately determine its mass. Mimas is the. closest satellite to Saturn. Observations of interactions between Mimas and the rings arc desired, as well as images of its large impact crater.

?.S Rings

Passes behind the rings provide the opportunity to use distortions in the radio signal from the spacecraft to determine ring composition and particle size. These passes are referred 10 as ring occultations. One particularly desirable. type of ring occultation occurs when the spacecraft passes directly across the middle of the planet (and the rings) from one side to the other. This is referred to as an "equatorial occultation". Several equatorial occultations arc. desired in the tour.

Viewing the rings from above is aiso important. At latitudes of S5 deg. or higher, the rings are visible around the entire disk of Saturn. Achieving an inclination of at least 55 deg. during the tour is therefore a high priority for ring science.

3. TOUR DESIGN CONCEPTS

During the tour, the gravitational fields of sate.ililcs are used to make large alterations in the trajectory. The concept of gravitational assist has been extensively discussed previously (Uphoff *et al*, 1979; Minovitch, 1972; Niehoff, 1971) and employed in previous missions. In brief, a satellite flyby can change the direction, but not the magnitude, of the orbiter's velocity relative to the satellite. This change. in the direction of the satellite-relative velocity vector can change. both the direction and the magnitude of the orbiter's velocity vector relative 10 the central body (Saturn, in the case of the Cassini tour). Since gravitational assist is fundamental 10 tour design, it is explored in greater detail in Ibis section.

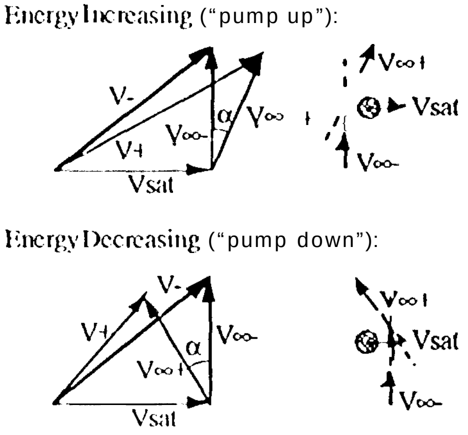
In the vicinity of a satellite, the orbiter's trajectory approximates a sale.iiitc-cchlcrc.ci hyperbola. The satellite-relative velocity vector along the incoming asymptote of this hyperbola (called V_∞) is computed by subtracting the satellite's Saturn-centered velocity from the orbiter's. The orbiter approaches from "infinity" (i.e., a point far enough from [he, satellite 10 be outside its gravitational influence) along the incoming asymptote of the hyperbola with a satellite-relative speed of V_∞. It gathers speed as it nears the satellite, attaining its greatest satellite-relative speed at closest approach. Its satellite-relative speed decreases to V_∞ as it departs along the outgoing asymptote. The angle between its incoming and outgoing asymptotes is referred 10 as the bending angle. The flyby altitude necessary to achieve a given bending angle is determined by the following equation:

$$\sin(\alpha/2) = 1/(1 + r_p V_\infty^2 / \mu) \qquad (1)$$

where α is the bending angle, r_p is the closest approach radius, V_∞ is the. satellite-relative speed at infinity along either asymptote, and μ is the sale.llilc's mass, The orbiter's Salulll-relative velocity after the flyby is then obtained by adding the satellite's Saturn-centered velocity 10 the orbiter's post-flyby V_∞.

The vector diagram shown in Figure 1 illustrates how a change in direction of the V_∞ vector can result in a change in both magnitude and direr.[ion of the orbiter's Saturn-centered velocity. In order 10 avoid violating the principle of conservation of energy, the satellite's Saturn-relative speed decreases if the flyby increases the orbiter's Saturn-relative speed (and vice versa). Because the satellite is so much more massive than the orbiter, the change in the satellite's speed is insignificant.

According to the above, equation, the more massive the satellite, the greater the bending angle. The only satellite of Saturn which is massive enough to use for orbit control during a tour is Titan. The masses of the others arc so small that even close flybys (within several hundred km) change the orbiter's orbit only slightly. Consequently, Cassini tours consist mostly of Titan flybys. This places restrictions on how the tour must be designed. Each Titan flyby must place the orbiter on a trajectory which leads back 10 Titan. The orbiter cannel be large.lut 10 a flyby of a satellite other than Titan unless the flyby lies almost along a return path 10 Titan. Otherwise, since. the gravitational influence of the other satellites is so small, the orbiter will not be able to return to Titan, and the tour cannot continue.



V-, V+	=	orbiter's velocity vector relative to Saturn (pre- and post-flyby)
Vsat	=	Titan's velocity vector relative to Saturn
V∞-, V∞+	=	orbiter's velocity vector relative to Titan along an asymptote (pre- and post-flyby)

Fig. 1. Vector diagram illustrating the use of gravitational assist to achieve "orbit pumping"

3.1 Pumping and cranking

Flybys can be used to achieve *orbit pumping*, that is, changing the orbital period with respect to Saturn, or *orbit cranking*, changing the orbit without changing its period. Increasing the period (referred to as "pumping up") with respect to the central body is accomplished by flying behind a satellite's trailing edge. Decreasing the period ("pumping down") involves flying ahead of its leading edge. Figure 1 illustrates orbit pumping.

Flybys which change the orbital period also rotate the line of apsides (the line connecting the periapsis and apoapsis points) and change the distance of the periapse from Saturn. The direction in which the line of apsides is rotated depends on whether the period is increased or decreased, and on whether the flyby occurs before Saturn-relative periapse ("inbound") or afterwards ("outbound"). Figure 2 shows that an outbound, period-reducing flyby (from orbit A to orbit B) rotates the line of apsides clockwise, and an outbound period-increasing flyby (from B to A) rotates the line counterclockwise. Rules for orbit rotation are listed in Table 1.

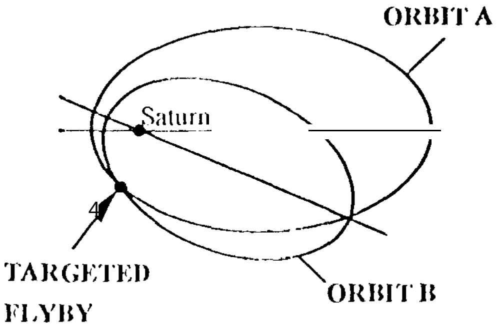


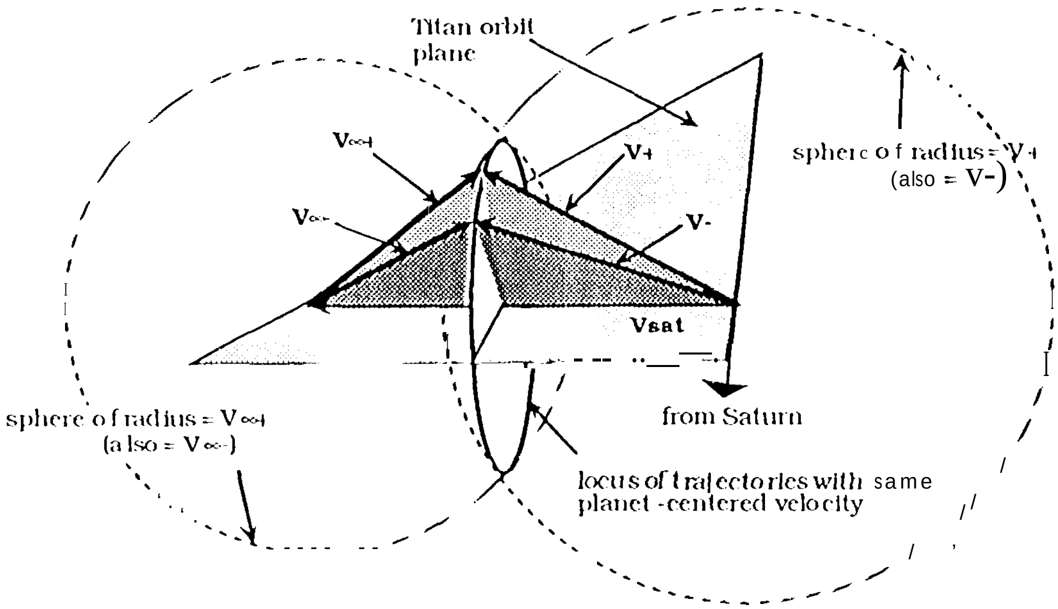
Fig. 2. Rotation of line of apsides.

Table 1: Orbit Rotation Rules

Flyby location	Energy (period) increasing flyby	Energy (period) decreasing flyby
Inbound (pre-periapse)	Clockwise	Counterclockwise
Outbound (post-periapse)	Counterclock wisr	Clockwise

Note: Clockwise rotation is in the direction from the initial orbit orientation (near the dawn terminator Of Saturn) toward the anti-sun direction.

Orbit cranking is illustrated in Figure 3. As the figure shows, in pure. orbit cranking the pm- and post-flyby velocity magnitudes relative to Saturn are the same, as are the pre- and post-flyby velocity magnitudes relative to the satellite. Since the Saturn-centered speeds are the same before and after the flyby, the pre- and post-flyby orbital periods are also the same.



V_-, V_+ = orbiter's velocity vector relative to Saturn (pre- and post-flyby)
V_{sat} = Titan's velocity vector relative to Saturn
$V_{\infty-}$, $V_{\infty+}$ = orbiter's velocity vector relative 10 Titan along an asymptote (pre- and post-flyby)

Fig. 3. Vector diagram illustrating the use of gravitational assist 10 achieve "orbit cranking".

The figure shows that in pure cranking, the locus of all possible V_∞ vectors after a flyby lie cm a sphere centered at the head of V_{sat}, and the locus of all possible V vectors lie cm a sphere centered at the tail of V_{sat}. Using a series of pure-cranking flybys, the heads of the V_∞ and V vectors can be placed anywhere on the circle of intersection of these two spheres. (A single, flyby can move the..sc vectors over only a small arc in the circle., due to bending angle limitations.)

Pure cranking changes orbital inclination and eccentricity. If the plane of the pre-flyby Saturn-centered orbit is near Saturn's equator, cranking mostly changes the orbital inclination. If the pre-flyby orbital plane is significantly inclined to the equator, cranking mostly change.s the eccentricity (i.e. periapse and apoapse radii change while the semimajor axis length remains constant). (Since the period Of an elliptical orbit depends on the length of the ellipse's semimajor axis, the semimajor axis length must be kept constant in order to keep period constant.)

If the orbital period (i.e.., V_a) and V_∞ arc held constant, pure orbit cranking can raise the inclination only m a maximum value which is described by the following relationship, taken from Uphoff *et al*:

$$i_{max} = \arccos [(V_{sat}^2 + V_-^2 - V_\infty^2) / 2V_{sat}V_-] \quad (2)$$

where i_{max} is the maximum inclination, Vs is the magnitude of Titan's velocity, V_- is the magnitude of the orbiter's Saturn-centered velocity before the flyby, and V_∞ is the hyperbolic excess speed (the magnitude of the V_∞ vector) with respect to Titan. As the. inclination gets higher, pare cranking causes greater changes in periapse/apoapse radii, and a smaller change in inclination. The theoretical maximum inclination is approached asymptotically. The first few flybys raise inclination most of the way, and the last fcw degrees of inclination require several flybys.

If V_∞ alone is held constant, the maximum inclination achievable with pure cranking change.s with orbital period, because varying period at constant V_∞ causes V. to change. The lower the period, the higher is the maximum inclination.

If the inclination to Saturn's equator is high, pure pumping changes the inclination significantly in addition to changing the period. Reducing the period increases the inclination; increasing the period reduces the inclination.

The gravitational assist obtained from a single satellite flyby may consist of pure pumping, pure cranking, or pumping and cranking components. The total bending angle. (obtained from both pumping and cranking components) must not exceed the value obtained from the bending equation at the minimum allowed flyby altitude.

Orbit pumping and cranking are discussed in detail in Uphoff, *et al.*

.7.2 Orbit orientation

The angle measured clockwise at Saturn from the. Saturn-sun line to the apoapse, referred to as the. "orbit orientation", is an important consideration for magnetospheric observations. The time available for observations of Saturn's lit side. decreases as the orbit rotates toward the arl[i-sari direction. Arrival conditions at Saturn fix the. initial orientation at about 90 deg. Due to the motion of Satui n around the sun, the orbit orientation increases with lime, at a rate of orientation is about 48 deg. Period-changing targeted flybys which rotate the iinc of apsides may be used 10 add to or subtract from this drift in orbit orientation. Figure 4, referred 10 as a "petal plot" because of the resemblance of the orbits to the petals of a flower, shows how the orbit rotates from the initial orientation to near the anti-sun dire.clion in the sample tour. In the coordinate system used in this figure, the direction 10 the sun is fixed.

2.3.3 Transfer orbits of 180 and 360 deg.

In general, the plane of the transfer orbit between any Iwo flybys is formed by the position vectors of the flybys from Saturn. If tile angle between the position vectors is other than 180 or 360 deg. (as is usually the case), the orbital plane formed by these two vectors is unique, and lies close to Titan's orbital plane, which is close to Saturn's equator. If the transfer angle is either 360 deg. (i.e.., the Iwo flybys occur at the same place), or 180 deg., an infinite number of orbital planes connect the flybys. In this case, the plane of the transfer orbit can be inclined significantly to the planet's equator. Any inclination can be chosen for the. transfer orbit, as long as sufficient bending is available from the flyby to get to that inclination.

It can aiso be said that if a spacecraft's orbital plane is significantly inclined to the equator, the transfer angle between any two flybys forming this orbital plane must be nearly 180 or 360 deg.

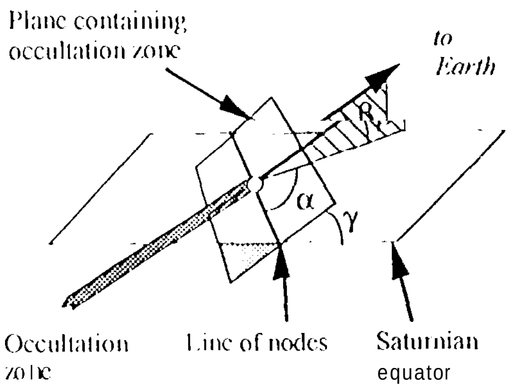
Fig. 4. "Petal plot" of sample Cassini tour, viewed from Saturn's north pole. Orbits are plotted in a relating coordinate. system, with the Saturn-Sun direction fixed at the top of the page..

3.4 *Inclination required for occultations of Saturn*

Saturn's equatorial plane is tilted 28 deg. to the ecliptic. The declination of Earth with respect to the Saturnian equator is zero only at two points in Saturn's orbit about the sun. To an Earth-based observer, the rings appear edge-on only at those two points. As it happens, the rings never appear edge-on during the tour. At the time of the Cassini spacecraft's arrival, the declination of Earth is -25 deg; four years later, it is -7 deg. Unless the declination of Earth is near zero, a spacecraft orbiting in Saturn's Equatorial plane does not pass behind Saturn as viewed from Earth. In this case, occultations of Earth by Saturn as viewed from the orbiter can be achieved only by inclining the orbital plane to the equator. Targeted satellite flybys are needed to raise the inclination to the required value.

The value of the inclination required to achieve a diametric occultation (that is, to pass directly behind the center of Saturn as viewed from Earth) is a function of the tilt of Saturn's equator viewed from Earth, and the angle between the Saturn-sun line and the line of nodes (the line connecting the points where the orbiter crosses Saturn's equator). An illustration of this relationship is provided in Figure 5. For a given equatorial tilt angle (i.e., at any point in Saturn's orbit), the inclination required to obtain a diametric occultation is minimized when the line of nodes is perpendicular to the Saturn-Earth line. Targeted satellite flybys are situated nearly along the line of nodes. It is desirable, therefore, to locate inclination-raising flybys nearly perpendicular to the Earth line in order to minimize the inclination (and therefore, the number of flybys) required to chain occultations.

Non-diametric occultations (passages behind Saturn, but not behind the center of the planet) can occur at inclinations several degrees from the value required for diametric occultations. These provide less information on Saturn's atmospheric structure than occultations close to or directly behind the center of the planet, however.



α = angle between line of nodes and Earth line, projected on Saturnian equator
β = declination of Earth
γ = inclination of plane containing occultation zone (orbital plane required to achieve occultation)

Fig. 5. Orbital geometry required to achieve occultations of Earth by Saturn, as viewed from the orbiter. The inclination required to achieve such an occultation is minimized when the line of nodes is perpendicular to the Earth line.

3.5 *Nontargeted flybys*

If the closest approach point during a flyby is far from the satellite, or if the satellite is small, the gravitational effect of the flyby can be small enough that the aimpoint at the flyby need not be tightly controlled. Such flybys are called "nontargeted". Flybys of Titan at distances greater than 25,000 km and flybys of satellites other than Titan at distances of greater than a few thousand km are considered nontargeted flybys. Flybys of satellites other than Titan at distances up to a few thousand km must be treated as "targeted" flybys to achieve scientific objectives, even though their gravitational influence is small. Opportunities to achieve nontargeted flybys of smaller satellites occur frequently during the tour. These are important for global imaging.

4. CONSTRAINTS

Tour design is constrained by many factors, some of which are due to the laws of orbital mechanics, and others of which are unrelated to those physical laws. Constraints are imposed due to the limits of hardware capabilities, instrument reliability, operational necessities, and budgetary concerns.

The arrival conditions at Saturn are fixed by the interplanetary trajectory. The orbiter arrives at Saturn on 1 July, 2004. This date was chosen for reasons of performance rind because it permits a flyby of Phoebe on approach to Saturn. The spacecraft arrives from an orbit near the ecliptic plane., at an inclination of approximately 17 deg. to Saturn's equator. A propulsive maneuver is executed to insert the orbiter into orbit about the planet.

The tour's maximum duration has been set at four years for budgetary reasons. The nominal tour must be finished four years after insertion into orbit about Saturn.

The orbiter must avoid crossing the ring plane within regions in the ring system in which impacts with particles could cause damage. in (his sample tour, ring plane crossings are allowed 10 occur only at 2.7 Saturn radii (RS) or greater, for this reason.

Titan's atmosphere imposes a minimum flyby altitude constraint. Thermal and attitude control considerations due to atmospheric drag arc the limiting factors. For the sample tour presented here, the lower altitude limit is assumed to be 950 km.

The lime. interval between targeted flybys must be large enough to allow detailed operational Impartation for the next encounter to occur. For the Galileo mission to Jupiter, this interval was set at 35 days. At this early stage in the Cassini project, all the details of operational preparation between encounters have not yet been decided upon. However, the advanced design of the Cassini ground system is expected to allow the minimum time between flybys to be as low as 16 days for several orbits, and probably in the range of 19-20 days for the rest of the tour.

Only a limited amount of propellant is available for tour operations. Propellant is used only to provide small adjustments to the trajectory necessary to navigate. the orbiter, to turn the orbiter in order to obtain scientific observations or to communicate with Earth.

s. METHODS AND SOFTWARE

While. the basic concepts used in tour design are straightforward, the process of arriving at an estimate of the [our trajectory precise enough [0 be considered flyable is heavily dependent on software and modern high-speed computing hardware. The design of a [our proceeds through lwo stages, initial design and optimization. The division of the process into these stages is a consequence of the wade.off between lilt initial need for fast (but not necessarily precise) trajectory computations for study purposes, and the eventual necessi(y of producing a precise estimate of the final trajectory chosen which minimizes propellant expenditure.

The initial design is done using highly interactive software which enables the user to evaluate various trajectory options quickly. The tour is designed one flyby at a time. At each flyby, the user chooses from a set of aimpoints presented by the program, each of which leads to a different subsequent flyby. At any point in the tour, if the user is dissatisfied with the trajectory, he or she can return to any previous flyby and choose a different set of encounters after that flyby. in this fashion, the user can quickly evaluate which trajectory options best achieve the scientific objectives of the (our without violating the mission constraints.

The result of the initial design stage is a mathematical representation of each orbit in the tour as an ellipse about Saturn (and, when near a flyby, a hyperbola about the flyby sale.liitc). Third-body effects such as the oblateness of Saturn and the gravitational effect of the Sun, which must be modelled in order to successfully fly the trajectory, arc so far unaccounted for. These arc modelled in the next stage, during which the trajectory is optimized. The initial representation of the trajectory is used as a "first guess," used 10 start the optimization process in a separate program. Flybys arc "control points" from which trajectory segments are numerically integrated forward and backward to "breakpoints" between flybys. The integrator includes multibody gravitational effects as well as some nongravitational effects. Initially, discontinuities in both position and velocity appear at the breakpoints. in order to achieve a final trajectory that is continuous in position, constraints are imposed on the optimization requiring that position discontinuities at breakpoints be zero. The velocity discontinuities represent maneuvers which arc. necessary 10 fly the trajectory. The optimization algorithm varies the flyby times and aimpoints on successive iterations 10 minimize the weighted sum of the ΔV's, in the process driving many maneuvers to zero. The estimate of total deterministic ΔV resulting from this process is almost atways less [ban that obtained from the initial design stage. The result of the optimization can be used as a nominal estimate of a flyable trajectory.

(). RESULTS

A brie.f summary of a sample tour, showing the sequence of targeted encounters and some. objectives accomplished at each encounter, is presented in Table 2. This tour contains 4? targeted Titan flybys and 6 of other satellites. Two targeted flybys of Enceladus and Dione occur, as well as one each of Iapetus and one of Rhea.

The first three Titan flybys reduce period and inclination. The orbiter's inclination is reduced to near zero with respect to Saturn's equator only after the third flyby; therefore, these three flybys must all take place at the same place in Titan's orbit. These period-rcxtucing flybys were designed to be inbound, rather than outbound, in order to accomplish the additional goal of rotating the line of apsides coumr-clockwise. This moves the apoapse toward the sun line in order to provide time for observations of Saturn's atmosphere.

After the inclination has been reduced to mar Saturn's equator, an outbound flyby of Titan occurs. Changing the fl yby from inbound to outbound here orients the line of nodes nearl y normal to the Earth line. As previousl y discussed, this geometry minimizes the inclination required to achieve an occultation of Saturn. Here, the minimum inclination required is about *22 deg.* The next two outbound flybys increase inclination to this value. The second of these also change.s period to 18.2 days. At this period, seven orbiter revolutions and eight Titan revolutions arc completed before the next Titan flyby, producing seven near-equatorial occupations of Earth by Saturn (one on cacb orbit). On all eight of these revolutions, the orbiter crosses Saturn's equator near Enceladus' orbit - on the fourth revolution, the, second targeted flyby of Enceladus occurs. Enceladus' gravity is too weak to displace inclination significantly from the value required to achieve occultations.

After accomplishing these occultations, inclination is once again reduced to near Saturn's equator and a series of alternating outbound/period -reducing and inbound/ Pcrirx-increasing flybys is used to rotate the orbit clockwise toward the magnetotail. An interruption of this sequence is allowed on the way to the magnetotail to accomplish a flyby of Iapetus on 4/16/2006. A slight increase in inclination (to about 2.7 deg.) is required to target to Iapetus. This inclination is rc.moved at the first Titan flyby after Iapetus. A magnetotail passage. occurs after the Titan flyby on 9/23/2006. This flyby raises inclination to shout 11 deg. in order to pass through Saturn's current sheet near apoapsis (at about 49 RS). At distance.s this far from Saturn, the current sheet is assumed to be swept away from Saturn's equatorial plane by the. solar wind.

Table 2: Summary of Sample Tour

Encounter	Date/Time yymmdd.hhmmss	Altitude (km)	lat. (deg)	Post-flyby period (days)	Post-flyby inclination to Saturn equator (deg.)	Comments
Titan	?.00111'27.141104	1200	25	47.9	15.4	Reduce period, inclination
Titan	20050114.093651	1 ?00	60	31.9	7.3	Reduce period, inclination
Titan	?.0050215.065109	12(K)	38	20.5	0.3	Reduce period, inclination
Enceladus	?.0050309.08s')3?	1O(K)	0	2.0.5	0.3	Enceladus imaging
Titan	20050331.203551	1487	45	16.0	11.4	Increase inc. for occultations
Titan	?005041 6.194249	1527	72	18.3	2.3.2.	8 Saturn/ring occultations
Enceladus	20050714.195557	5(K)	-40	18.3	2.3.?.	Enceladus imaging
Titan	2.005082?..092112	950	-73	16.0	9.7	Reduce inclination
Titan	20050907.082333	950	-3?	23.2	0.4	Reduce inclination
Titan	20050926.220230	1901	1	39.3	0.4	Rotate clockwise
Titan	20051108.212959	1642	0	23.2'	0.4	Rotate clockwise.
Titan	?.00511?8.110046	1837	5	39.3	1.0	Rotate clockwise
"Pilan	20060110.1012.00	15453	67	37.4	2.7	Target m Iapetus
Iapetus	2.0060418.035 10?	681	-14	36.7	2.1	Iapetus imaging
Titan	20060501.040051	1970	-10	23.0	0.3	Rotate clockwise
Titan	?CM052.I.13S937	1617	0	39.5	0.4	Rotate clockwise
Titan	20060703.161 545	1508	0	2.3.0	0.4	Rotate clockwise
Titan	20060723.014705	1570	0	39.2	0.4	Rotate clockwise
Titan	20060904 .030245	1734	-1	2.3.2	0.4	Rota[c. clockwise
Titan	20060923.153919	2575	84	24.0	10.8	Magnetotail pas.sage
Titan	2.0061110.113209	95(J	23	16.0	19.8	Increase inclination
Titan	2OO61I?L.1O4355	950	74	16.0	34.4	Increase inclination
Titan	200612 .12..09?419	950	64	16.0	44.6	Increase inclination
Titan	200612.28.075816	950	54	16.0	51.5	Increase inclination
Titan	20070113.063114	950	44	16.0	56.1	Increase inclination
Titan	20070 129.0S0406	950	34	16.0	59.2	Increase inclination
Titan	20070 ?14.033929	950	32	18.1	59.5	180-deg. transfer
Titan	20070309.2352.20	950	30	16.0	59.3	Reduce inclination
Titan	2007032.5.222913	950	32	16.0	56.8	Reduce inclination
Titan	20070410.210338	950	41	15.9	53.1	Reduce inclination
Titan	20070426. 193724	950	50	15.9	47.7	Reduce inclination
Titan	2.(K)") 0512.181016	950	59	15.9	40.1	Reduce inclination
Titan	20070528.164245	950	68	15.9	2.9.4	Reduce inclination
Titan	2.0070613.151921	9s0	77	16.0	15.4	Reduce inclination
Titan	20070629.141317"	1104	70	18.0	0.6	Reduce inc., target to Rhea
Rhea	20070803.112738	5(K)	69	17.9	0.3	Rhea imaging
Titan	20070819.051944	3276	0	23.9	0.3	Target to Dione
Dione	20070913.140443	10(K)	39	2.4.?	o.?	Dione imaging
Titan	2.0071006 .004447	9983	-5	2.0.6	0.5	Target to Dione
Dione	2007 102%.172607	2840	-62	20.6	0.5	Dione imaging
Titan	20071119.190610	950	-50	16.()	13.2.	Position node for max. inc. sequence
Titan	?007 12.05.180447	950	-78	15.9	28.1	Increase inclination
Titan	20071221.164457	9s0	-69	15.9	39.3	Increase inclination
Titan	2.0080106. I5I537	950	-10	11.9	47.9	Increase inclination
Titan	20080223.103542	950	-34	10.6	56.7	Increase inclination
Titan	20080326.073537	950	-26	9.6	63.3	Increase inclination
Titan	200805 13.030955	950	16	8.0	69.3	Increase inclination
Titan	20080529.013409	950	10	7.1	74.8	Increase inclination

This inclination-raising flyby also begins a 180-deg. transfer sequence. The next flyby (on 1 1/10/2006) reduces period to 16 days as well as raising inclination. During the next 6 flybys, period is kept contant at 16 days while inclination is raised as much as possible. As inclination is raised, periapsis radius increases and apoapsis radius decreases until the orbit is nearly circularized at an inclination of about 60 deg. The orbiter's trajectory then crosses Titan's orbit at not one., but two points (the ascending and descending nodes), making possible a 180-deg. transfer from an inbound Titan flyby to an outbound Titan flyby. After this 180-deg. transfer is accomplished, the next seven Titan flybys, all of which arc outbound, arc used to reduce inclination as quickly as possible to near Saturn's equator. After reaching near.c.qllaloriai inclination, the next three flybys arc Used to target to icy satellites (Rhea once., Dione twice).

The orbiter is then targeted to an outbound Titan flyby (On 1 1/19/-2007) placing the line of nodes close to the sun line. Starting with this flyby, the rest of the. tour is devoted to a sequence of flybys designed to raise inclination as high as possible (in this case, to about 75 deg.) Maximum inclination is desired for ring obser vations and in-situ field and particle measurements. in this sample tour, the orbits during this maximum-incl ination flyby sequence arc oriented nearly toward the sun, away from the. magnetotail, in order to assure several occultations of Earth by Saturn and the rings at close distances during this sequence.

During this flyby sequence, first orbit cranking, and the.n orbit pumping (after a moderate inclination has been achieved) arc used 10 increase inclination, eventually reducing the orbit period to 7.1 days (9 orbiter re volutions : 4 Titan revolutions). The closest approach altitudes during this sequence arc kept at the minimum allowed value. in order to maximize gravitational assist at each flyby.

When the line of node.s is as close to the sun line as it is in this sample tour, occultations of Earth by Saturn arc achieved on c.very orbit after the minimum inclination required to achieve occultations is exceeded (which occurs after the first few flybys). When the inclination is much greater than the. required minimum, the entry and exit points arc nearer Saturn's pole regions than its equator, These occultations provide valuable. information on Saturn's atmosphere; however, their entry and exit points arc too far from the equator to allow passage behind the rings. in all, the sample tour contains 36 occultations of Earth by Saturn, 7 of which arc near-equatorial. and 17 of which occur during the maximum-inclination sequence. The remaining 12 arc grazing occultations which occur during other portions of the tour.

Fifteen occultations of Earth by Titan occur during the. sample tour, allowing probing of Titan's atmosphere. The 42 Titan flybys provide opportunities for radar coverage of various portions of Titan. Because of conflicting scientific require.rncnts and orbiter operating constraints, radar swaths cannot be taken at c.very flyby. Similar flybys (for example, inbound/period-reducing flybys) have similar ground tracks.

The tour ends on 1 July, 2008, 4 years after insertion into orbit about Saturn. The aimpoint at the last flyby, on 5/?9/2008, is chosen to target the orbiter to a subsequent Titan flyby to provide. the. opportunity to proceed with more flybys during an extended mission, if resources allow.

7. CONCLUSIONS

The diver.sc scientific objectives and multiple constraints of the. Cassini mission make. it an interesting challenge 10 design a sate.llilc tour which can fulfill the promise of this exciting mission. The large experience base in tour design accumulated during the Galileo mission to Jupiter helps in meeting this challenge. However, di fferences between the, Saturnian and Jovian environments and the scientific objectives of Cassini and Galileo necessitate development of new tour design techniques for Cassini. The sample tour presented here. illustrates methods of designing Cassini tours which achieve the mission's scientific objectives while meeting mission-imposed constraints. Trade-offs identified during the course of designing this sample. tour will be examined further in preparation for design of the final Cassini tour.

8. ACKNOWLEDGMENTS

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SPK File: t18-1.5.00K.bsp. View from Saturn North Pole. Sun at Top

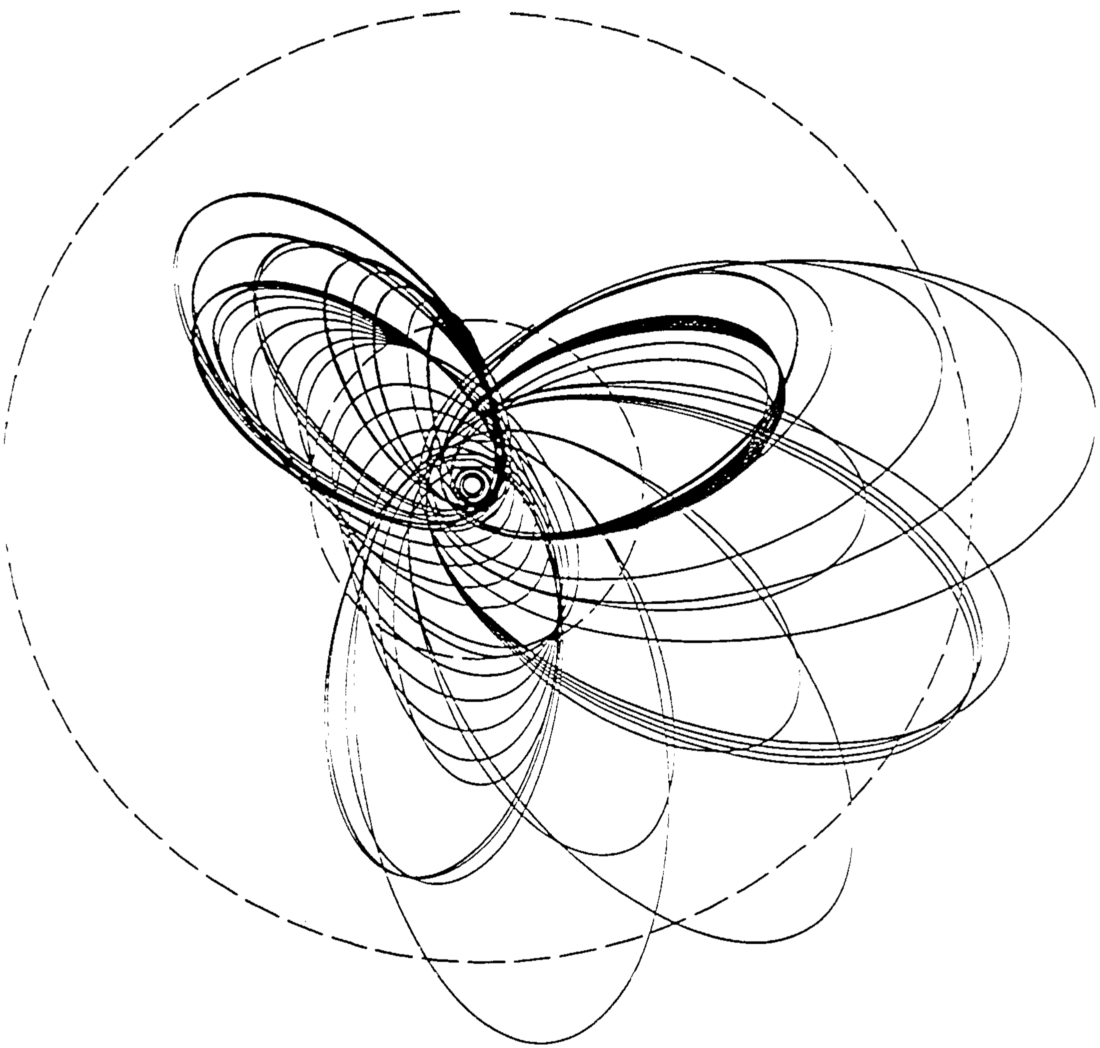


Fig. 4

SPK File: t18-1.STOCK.bsp, View From Saturn North Pole, Sun at Top

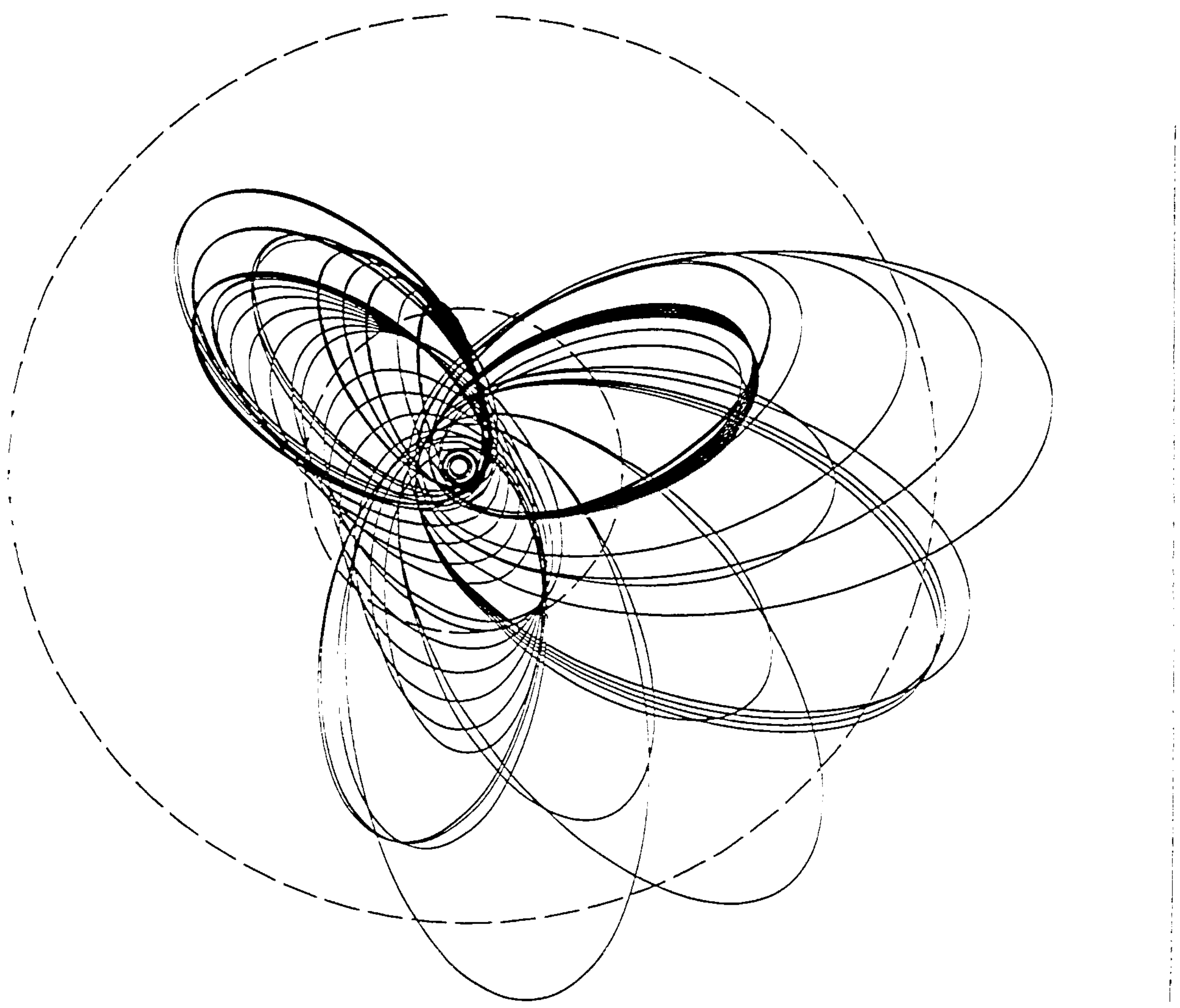
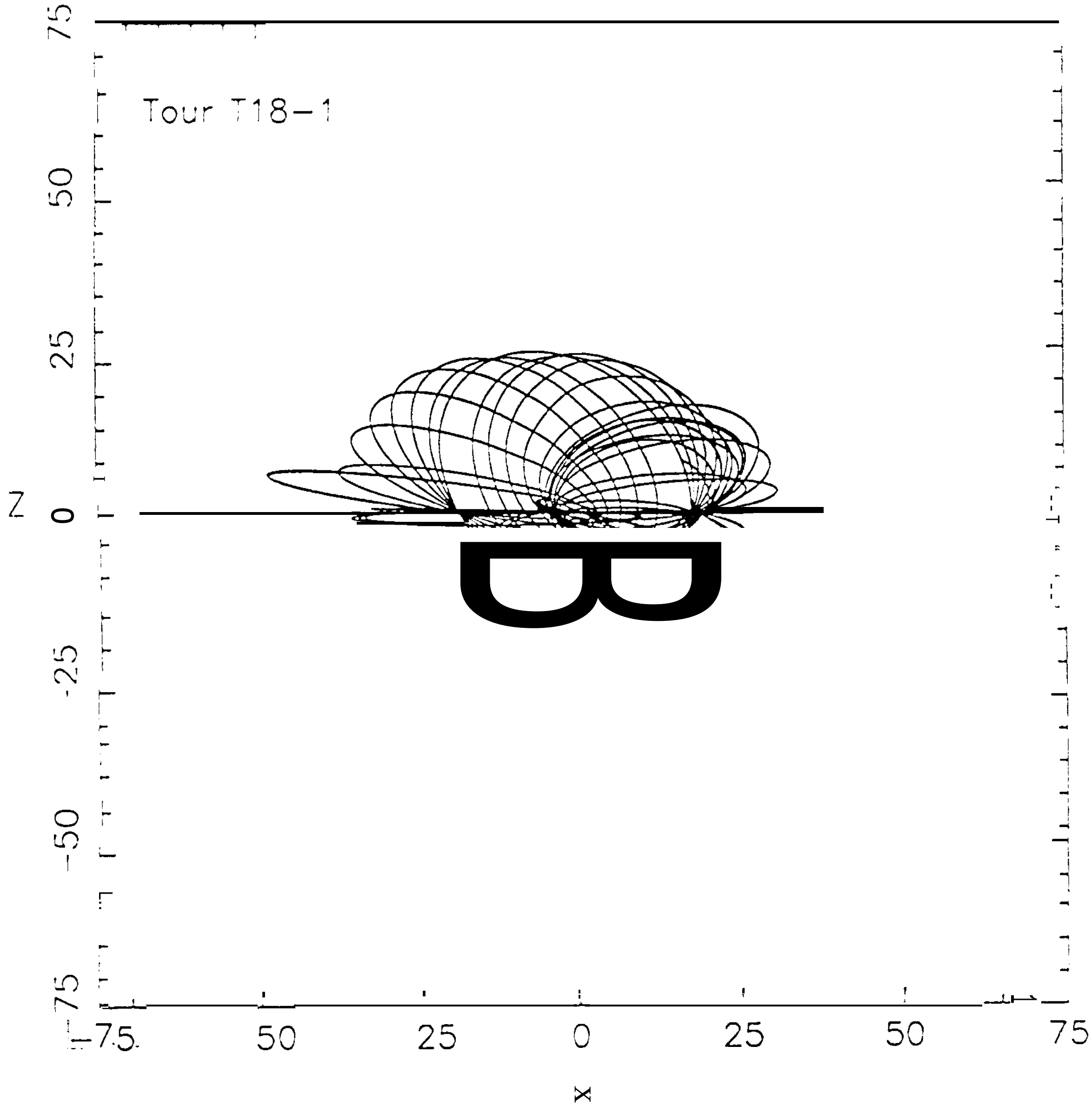


Fig 4



Tour T18-1
Z
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50
25
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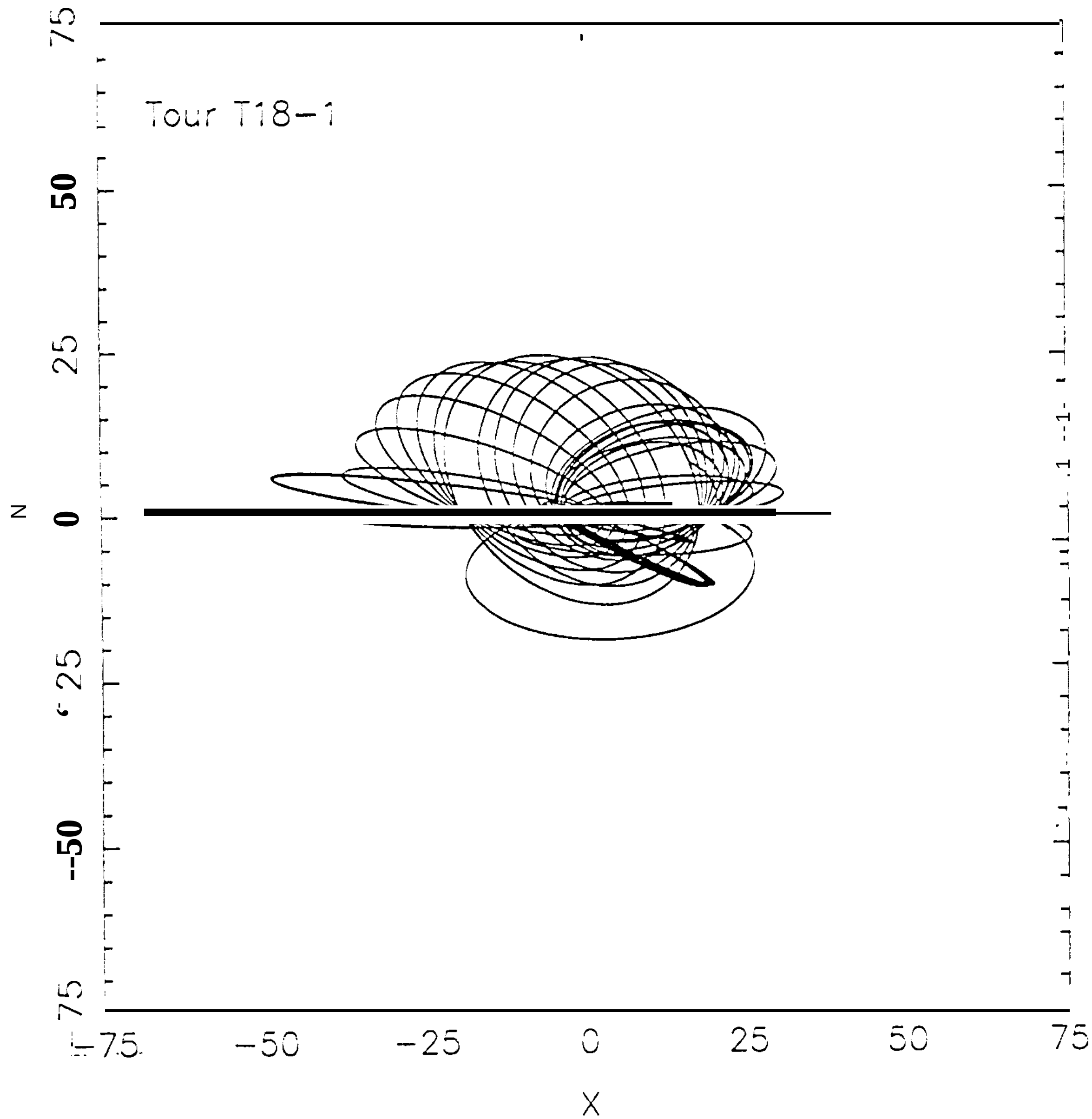
-25
−50
-75
75
50
25
0
25
50
75
B



Tour T18-1
N
X